Carderock Division
Naval Surface Warfare Center
9500 MacArthur Blvd.
West Bethesda, MD 20817-5700

NSWCCD-70-TR-2000/038 February 2000
Signatures Directorate
Research and Development Report

Structural Fuzzies At Sea

by

G. Maidanik

DTIC QUALITY INSPECTED 2

20000509 198

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS None

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release. Distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	

4. PERFORMING ORGANIZATION REPORT NUMBER(S) NSWCCD-70-TR—2000/038	5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Carderock Division, NSWC	6b. OFFICE SYMBOL (if applicable) Code 7030	7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State, and ZIP Code) 9500 MacArthur Blvd. West Bethesda, MD 20817-5700	7b. ADDRESS (City, State, and ZIP Code)

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

Structural Fuzzies At Sea

12. PERSONAL AUTHOR(S)

G. Maidanik

13a. TYPE OF REPORT Research & Development	13b. TIME COVERED FROM 010300 TO 030100	14. DATE OF REPORT (Year, Month, Day) 2000 March 1	15. PAGE COUNT 54

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Statistical Energy Analyses (SEA) Structural Fuzzy Modal Density Structural Damping

18. ABSTRACT (Continue on reverse if necessary and identify by block number)

A rudimentary statistical energy analysis (SEA) can be employed to decipher the functioning of structural fuzzies. A structural fuzzy is a device that, when coupled strongly to a structure, increases the damping of that structure. A structural fuzzy must be endowed with a modal density and structural damping that by far exceeds those of the structure to which it is strongly coupled.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Maidanik, G.	22b. TELEPHONE (Including Area Code) (301) 227-1292	22c. OFFICE SYMBOL NSWCCD 7030

DD Form 1473, JUN 86 · Previous editions are obsolete ·

ABSTRACT

A rudimentary statistical energy analysis (SEA) can be employed to decipher the functioning of structural fuzzies. A structural fuzzy is a device that, when coupled strongly to a structure, increases the damping of that structure. A structural fuzzy must be endowed with a modal density and structural damping that by far exceeds those of the structure to which it is strongly coupled.

Friday, October 15, 1999 11:00
Room 210
Photonic Center
8 St. Mary's Street
Boston, MA 02215

This report is based on the seminar given at Boston University as stated above. Viewgraphs are presented on the right and comments relevant to that viewgraph are placed on the left. A few of the remarks made by the audience are included without reference. Nonetheless, the author is thankful for these participations by the attendees.

A Note:

Recently a full fledged effort has been launched to develop analyses which yield information transcending that which is issued by SEA. In particular, there are claims that the information issued by SEA in the low and mid-frequency ranges is deemed inadequate for certain response descriptions and noise control purposes. These issues were deliberately forfeited by assumptions imposed during the development of SEA and, therefore, they lie, by definition, beyond the scope of SEA. The assumptions, so conceived, render SEA a more tractable analysis. It is, therefore, impertinent to blame SEA for any inadequacies resulting from these forfeits. Moreover, there are those who interpret the results in the low and mid-frequency ranges by the failure of SEA to yield information that is suppressed apriori in the development of SEA. Yet, by definition, SEA can and will yield the information that it is designed to yield, independent of the frequency range. Notwithstanding that in a given frequency region, the deviation from the mean-value may fluctuate more and more as the violation of the condition of the modal overlap becomes more severe [1,2]. In SEA the mean-value is the fundamental description. Indeed, the very strength of SEA is that it chooses the right thing (details) to be ignorant about as a way to learn something (mean-values). It takes chutzpah to ascertain the in the low and mid-frequency ranges by the apparent failure of SEA to account for phenomena that lie outside its scope. It transpires that the low and mid-frequency ranges are often determined by the failure of those who profess to understand what SEA says is, is!

Revisiting Elements in Statistical Energy Analysis (SEA)
G. Maidanik, NSWCCD (DTMB)

AGENDA

- A brief review of SEA is presented.

- The modifications in SEA due to the influence of strong couplings among the substructures are discussed.

- Some remedial modifications to SEA are heuristically proposed.

- Two noise control problems are described and interpreted in terms of SEA:

  1. Control of loss factors (dissipations) in pipe-like structures containing beads. The beads are modeled to be a fluid of low sound speed and of high damping.

  2. Control of vibrations by increasing damping and isolation. In particular, a note is taken of the supplementarity of damping and isolation in vibration control.

Mathematical Symbols

Scalar $\qquad\qquad v$

Vector of Rank N $\qquad \underset{\sim}{v} = \left\{ \begin{array}{c} v_1 \\ v_2 \\ \vdots \\ v_j \\ \vdots \\ v_N \end{array} \right\} = \{v_j\}$

Transposed $\qquad \underset{\sim}{v}^{\dagger} = \{v_1, v_2, \ldots v_j \ldots v_N\}$

Complex conjugate $\underset{\sim}{v}^* = \{v_j^*\}$

$\underset{\sim}{v}^{\dagger}\, \underset{\sim}{v}^* \equiv$ a Scalar ; $\quad \underset{\sim}{v}^*\, \underset{\sim}{v}^{\dagger} \equiv$ a Matrix

Matrix of
Rank N $\qquad \underset{\approx}{z} = \begin{pmatrix} z_{11} & z_{12} & \cdots & z_{1j} & \cdots & z_{1N} \\ z_{21} & z_{22} & \cdots & z_{2j} & \cdots & z_{2N} \\ \vdots & \vdots & & \vdots & & \vdots \\ z_{j1} & \vdots & \cdots & z_{jj} & \cdots & z_{jN} \\ \vdots & \vdots & & \vdots & & \vdots \\ z_{N1} & \vdots & \cdots & z_{Nj} & \cdots & z_{NN} \end{pmatrix} = (z_{jl})$

e.g.,

$$\underset{\approx}{z} = \left(\left(z_{jj}\delta_{jl} - z_{jl}(1-\delta_{jl})\right)\right)$$

Impedance Matrix Eq. $\qquad$ Admittance Matrix Eq.

$$\underset{\approx}{z}\,\underset{\sim}{v} = \underset{\sim}{F} \qquad\qquad\qquad \underset{\sim}{v} = \underset{\approx}{y}\,\underset{\sim}{F}$$

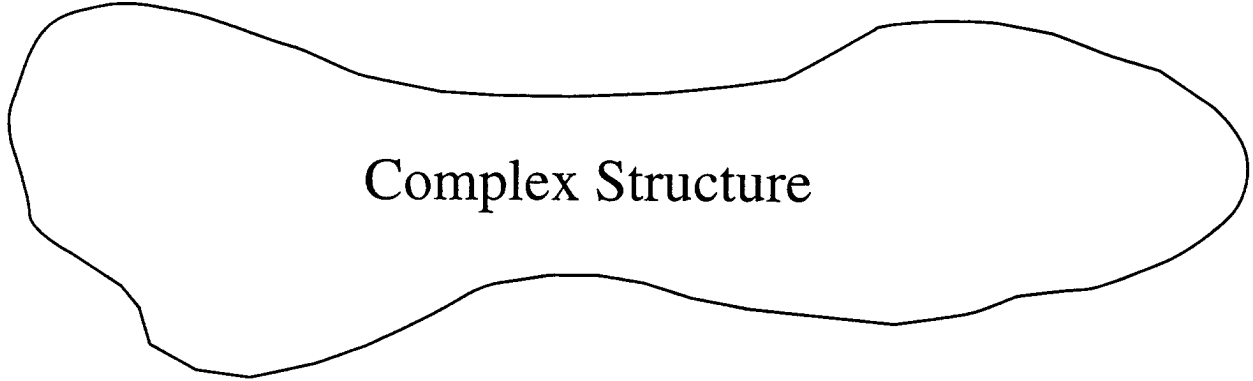where symbolically $\underset{\approx}{y} = (\underset{\approx}{z})^{-1}$

Viewgraph 3

The division of a complex structure into constituent substructures is crucial in SEA. Yet, rarely is this division discussed, and specifications for it are rarely laid down. In part, the reluctance stems from the belief that "An arbitrariness (non-uniqueness) in the service of a good approximation is not a vice, it is a useful device" and, in part, apriori rules are difficult to state. In addition, SEA is a function of the frequency (steady state) variable (ω) or the temporal (transient state variable (t). The division may, therefore, be dependent on (ω) or (t); e.g., a division at (ω_1) may be different from a division at (ω_2) where $\omega_1 \neq \omega_2$. That dependence of the division is seldom discussed but its significance is here recognized. In the final analysis, it turns out that experience is often the best guide to this division. Needless to state, the larger the number of substructures the higher is the frequency at which the fundamental resonance frequency lies, and the higher is the rank of the matrix equation of motion at SEA. Therefore, the higher the number of substructures the higher is the frequency of validity, and the more difficult is the manipulations of the equation of motion. On the other hand, the smaller the number of substructures the more details are suppressed; excessive suppression of details may render the equation of motion moot and without substance.

None of these extremes are happy circumstances. It is hoped, in this connection, that some idea for the appropriate division procedure will emerge in the reading of this report.
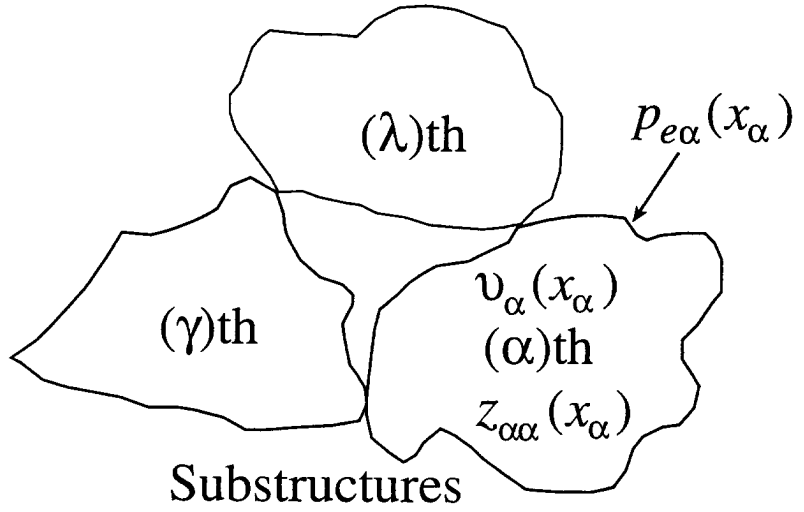
Statistical Energy Analysis (SEA)

Complex Structure

$$z(x)\ v(x)\ =\ p_e(x)\ \mid\ x \to \underset{\sim}{x}\ ;\ t\ \text{or}\ \omega$$

$$\underset{\approx}{z}(\underset{\sim}{x})\ \underset{\sim}{v}(\underset{\sim}{x})\ =\ \underset{\sim}{p}_e(\underset{\sim}{x})$$

(λ)th $p_{e\alpha}(x_\alpha)$

(γ)th

$v_\alpha(x_\alpha)$
(α)th
$z_{\alpha\alpha}(x_\alpha)$

$$\underset{\sim}{x}\ =\ \{x_\alpha\}$$

$$\underset{\sim}{v}(\underset{\sim}{x})\ =\ \{v_\alpha(x_\alpha)\}$$

$$\underset{\sim}{p}_e(\underset{\sim}{x})\ =\ \{p_{e\alpha}(x_\alpha)\}$$

Substructures

$$\underset{\approx}{z}(\underset{\sim}{x})\ =\ \left(z_{\alpha\alpha}(x_\alpha)\delta_{\alpha\gamma} - \int dx_\gamma z_{\alpha\gamma}(x_\alpha \mid x_\gamma)(1-\delta_{\alpha\gamma})\right)$$

x_α is a vector that spans the dimensionality of the (α)th substructure. Thus, if the (α)th substructure is one-dimensional, x_α is a scalar. If it is two-dimensional, x_α is a two-vector and if it is three dimensional, x_α is a three-vector. The dependence of quantities on the time variable (t) or on the frequency variable (ω) is implicit in this scalar or matrix impedance equation of motion.

Viewgraph 4

A generic division of a complex structure into substructures is represented in Viewgraph (3). The choice of the division must, however, be compatible with the requirement that the self-impedance operator of the substructures; e.g., $z_{\alpha\alpha}(x_\alpha)$ of the (α)th substructure, be eigenoperators so that a complete set of orthogonal mode shape functions may be assigned to each substructure; e.g., $\phi_{\alpha j}(x_\alpha)$ are assigned to the αth substructure as depicted in Viewgraph (3). In this manner the individual mode shape vectors and the overall mode shape vector may be defined; $\underset{\sim}{\phi}_{\alpha j}(x_\alpha) = \{\phi_{\alpha j}(x_\alpha)\}$ and $\underset{\sim}{\phi}(\underset{\sim}{x}) = \{\underset{\sim}{\phi}_\alpha(x_\alpha)\}$, respectively.

The choice for the self-impedance operators and, therefore, for the coupling impedance operators and the mode shape functions is not unique; they may be chosen in a variety of ways, however, each way may be related to the others. With experience the better choices may be identified.

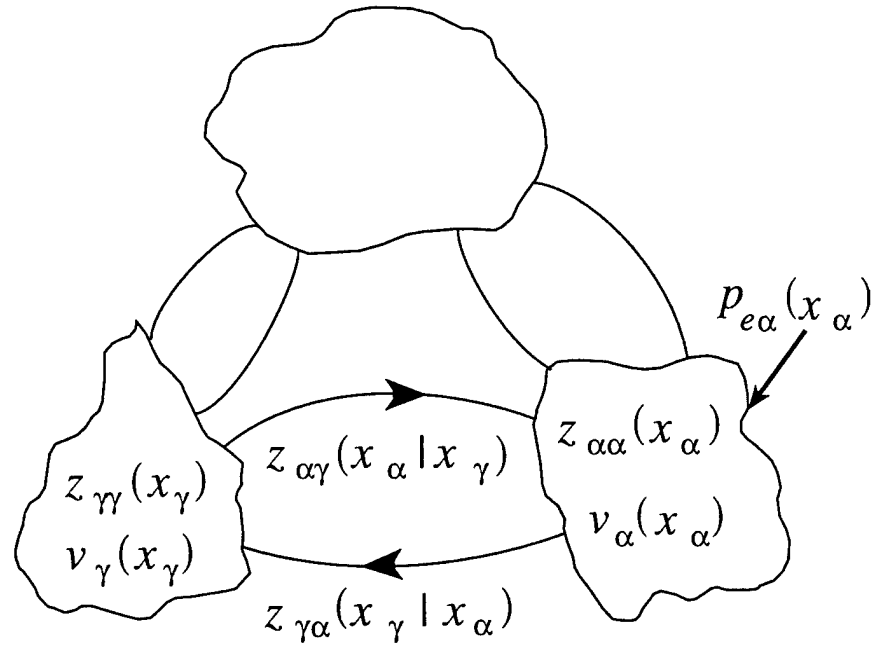A complex composed of a number of coupled dynamic systems

$$\underset{\approx}{z}(\underset{\sim}{x}) \; \underset{\sim}{v}(\underset{\sim}{x}) = \underset{\sim}{p}_e(\underset{\sim}{x})$$

$$\underset{\sim}{x} = \{x_\alpha\}$$

$$\underset{\sim}{v}(\underset{\sim}{x}) = \{v_\alpha(x_\alpha)\}$$

$$\underset{\sim}{p}_e(\underset{\sim}{x}) = \{p_{e\alpha}(x_\alpha)\}$$

$$\underset{\approx}{z}(\underset{\sim}{x}) = \left(z_{\alpha\alpha}(x_\alpha)\delta_{\alpha\gamma} - \int dx_\gamma z_{\alpha\gamma}(x_\alpha | x_\gamma)(1 - \delta_{\alpha\gamma}) \right)$$

The rank of the equation of motion is equal to (N), the number of dynamic systems in the complex.

The self-impedances; e.g., $z_{\alpha\alpha}(x_\alpha)$, are eigenoperators in the sense that

$$z_{\alpha\alpha}(x_\alpha)\varphi_{\alpha j}(x_\alpha) = z_{\alpha j \alpha j}\,\varphi_{\alpha j}(x_\alpha) \;\; ;$$

$$\underset{\sim}{\varphi}_\alpha(x_\alpha) = \{\varphi_{\alpha j}(x_\alpha)\} \;\; ; \;\; \underset{\sim}{\varphi}(\underset{\sim}{x}) = \{\underset{\sim}{\varphi}_\alpha(x_\alpha)\}$$

Viewgraph 5

Employing the chosen complete and orthogonal sets of mode shape functions, the modal equation of motion may be derived as stated in Viewgraph (5). The rank of this modal equation may be quite large, especially at the higher frequency ranges. Nonetheless, if this equation can be solved for the modal response ($\underset{\sim}{v}$) and the spatial dependence of the mode shape functions is retained, the response $v_\alpha(x_\alpha)$, of typically the α th substructure, may be restored and stated as prescribed in Viewgraph (6).

Modal decomposition $\longrightarrow$ removal of the spatial dependence in the equation of motion $\longrightarrow$ modal equation of motion

$$\underset{\approx}{z}\,\underset{\sim}{v} = \underset{\sim}{p}_e \quad ; \quad \underset{\approx}{z} = \left(\left(\underset{\approx}{z}_{\alpha\alpha}\,\underset{\approx}{\delta}_{\alpha\gamma} - \underset{\approx}{z}_{\alpha\gamma}(\underset{\approx}{1} - \underset{\approx}{\delta}_{\alpha\alpha})\right)\right) \quad ;$$

$$\underset{\sim}{v} = \{\underset{\sim}{v}_\alpha\} \quad ; \quad \underset{\sim}{v}_\alpha = \{v_{\alpha j}\} \; ; \; \underset{\sim}{p}_e = \{\underset{\sim}{p}_{e\alpha}\} \; ; \; \underset{\sim}{p}_{e\alpha} = \{p_{e\alpha j}\} \quad ;$$

$$\underset{\approx}{z}_{\alpha\alpha} = (z_{\alpha j \alpha j}\,\delta_{jl}) \quad ; \quad \underset{\approx}{z}_{\alpha\gamma} = (z_{\alpha j \gamma q}) \quad ;$$

$$z_{\alpha j \gamma q} = \int dx_\gamma \int dx_\alpha \; \varphi_{\alpha j}(x_\alpha) z_{\alpha\gamma}(x_\alpha | x_\gamma) \; \varphi_{\gamma q}(x_\gamma) \quad .$$

The rank of the modal equation of motion is equal to $\sum_\alpha N_\alpha$, where N_α is the number of all relevant modes in the $(\alpha)th$ dynamic system.

Viewgraph 6

Again, the modal equations of motion are stated in Viewgraph (6). Since a set of

mode shapes is assumed to be complete and orthogonal, the modes in each substructure

are not coupled, couplings occur only between modes belonging to different substructures

(dynamic systems).

The inverse equation of motion is stated in order to indicate that if $(\underset{\approx}{z})$ is known,

its inverse $(\underset{\approx}{y})$ may be used to directly determine the response vector $(\underset{\sim}{v})$ once the

external drive vector $(\underset{\sim}{p}_e)$ is given.

The high rank of the impedance matrix or the admittance matrix modal equation

of motion may render a solution well nigh impossible. Means to reducing the rank may

thus be advantageous, even at the expense of forfeiting details.

Recovery of the spatial dependence

$$v_\alpha(x_\alpha) = \underset{\sim}{v}_\alpha^\dagger \cdot \underset{\sim}{\varphi}_\alpha(x_\alpha) \quad ; \quad p_{e\alpha}(\underset{\sim}{x}) = \underset{\sim}{p}_{e\alpha}^\dagger \cdot \underset{\sim}{\varphi}_\alpha(x_\alpha)$$

Thus, if the eigenvectors $\underset{\sim}{\varphi}_\alpha(x_\alpha)$ are appropriately stored, they can be used in this reconstitution when desired.

Modal equation of motion

$$\underset{\approx}{z}\,\underset{\sim}{v} = \underset{\sim}{P}_e \quad ; \quad \underset{\approx}{z} = \left(\underset{\approx}{z}_{\alpha\alpha}\underset{\approx}{\delta}_{\alpha\gamma} - \underset{\approx}{z}_{\alpha\gamma}(1-\underset{\approx}{\delta}_{\alpha\gamma})\right)$$

$$\underset{\approx}{z}_{aa} = \left(z_{ajaj}\delta_{jl}\right) \qquad\qquad \underset{\approx}{z}_{a\gamma} = \left(z_{aj\gamma q}\right)$$

No modal couplings in   Modal couplings across

a dynamic system   dynamic systems

$$\underset{\sim}{v} = \underset{\approx}{y}\,\underset{\sim}{P}_e \quad ; \quad \underset{\sim}{v} = \{\underset{\sim}{v}_\alpha\} \quad ; \quad \underset{\approx}{y} = (\underset{\approx}{z})^{-1} \quad ; \quad \underset{\sim}{P}_e = \{\underset{\sim}{P}_{e\alpha}\}$$

Viewgraph 7

The forfeiting of details starts with the abandonment of spatial information within each substructure; only the response of each mode is registered without heed to its spatial distribution -- the mode is, then, reduced to be a simple harmonic oscillator. Once the spatial information is forfeited, the phase of each harmonic oscillator loses its significance. If forfeiting the phases can be advantaged in the effort to reduce the rank of the modal equation of motion, let it be done. The phases are forfeited by quadratizing the modal equation, as stated in Viewgraph (7). Then, the real part of the resulting equation is executed, again, as stated in Viewgraph (7). The fundamental statement of SEA is presented. This statement is extrapolated from findings pertaining to the interaction between two linear harmonic oscillators [2,3].

Return to the modal equation of motion

$$\underset{\approx}{z}\,\underset{\sim}{v} = \underset{\sim}{P}_e \;\; ; \;\; z_{\alpha j \alpha j}v_{\alpha j} - \sum_{\gamma}\sum_{q} z_{\alpha j \gamma q}v_{\gamma q}(1-\delta_{\alpha \gamma}) = P_{e\alpha j} \;\; .$$

In this equation $\underset{\sim}{\varphi}\,(\underset{\sim}{x})$ is forfeited by spatial averaging.

Now the phases in $\underset{\sim}{v}$ are forfeited by quadratizing the

modal equation

$$z_{\alpha j \alpha j}|v_{\alpha j}|^2 - \sum_{\gamma}\sum_{q}(v_{\alpha j})^* z_{\alpha j \gamma q}v_{\gamma q}(1-\delta_{\alpha \gamma}) = (v_{\alpha j})^* P_{e\alpha j} \;.$$

Take the real part of and normalize

$$\eta_{\alpha j \alpha j}\varepsilon_{\alpha j} - \mathrm{Re}\{\underbrace{\sum_{\gamma}\sum_{q}(v_{\alpha j})^*(z_{\alpha j \gamma q}/\omega)(v_{\gamma q})(1-\delta_{\alpha \gamma})}\} = (\pi_{e\alpha j}/\omega)$$

$$+ \sum_{\gamma}\sum_{q}\eta_{\alpha j \gamma q}(\varepsilon_{\alpha j}-\varepsilon_{\gamma q})\,(1-\delta_{\alpha \gamma})$$

This is the fundamental statement of SEA with

$$\eta_{\alpha j \gamma q} = \eta_{\gamma q \alpha j} = \begin{cases} \text{Small if } \omega_{\alpha j} \neq \omega_{\gamma q} \\[2mm] \text{Large if } \omega_{\alpha j} \simeq \omega_{\gamma q} \end{cases}$$

Viewgraph 8

The definition of the modal energy $(\mathcal{E}_{\alpha j})$ of the (j)th mode (harmonic oscillator) in the (α)th substructure is stated in terms of the mass (M_α) of that substructure. The quantity $(\mathcal{E}_{K\alpha j})$ is the kinetic modal energy stored in the referenced mode. The real part of $\{(v_{\alpha j})^* p_{e\alpha j}\}$ is equated to the external power input into the (j)th mode in the (α)th substructure.
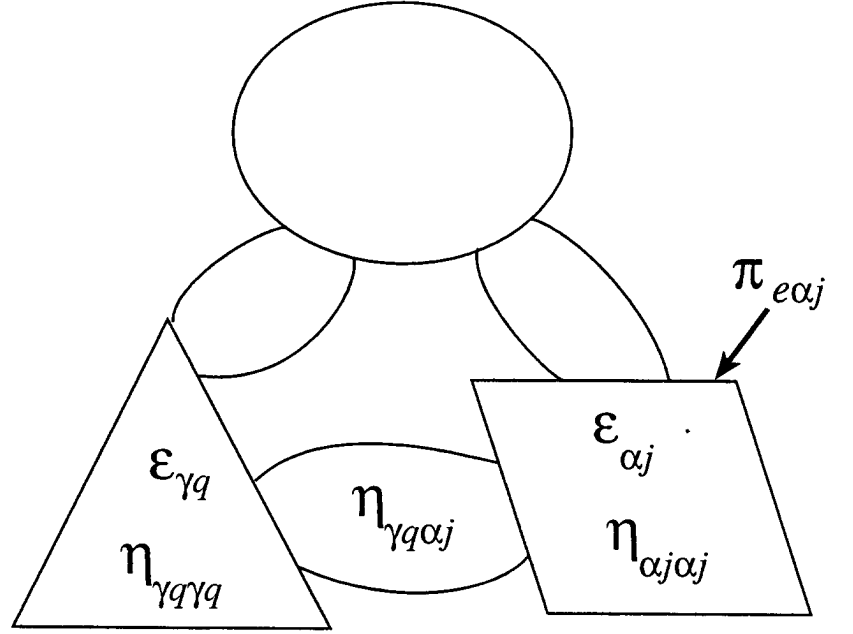
The span function is defined in terms of a frequency bandwidth $(\Delta\omega)$ centered about (ω) that includes all modes within it. Thus, $\langle \cdots \rangle_{\Delta\omega}$ represents frequency averaging over the quantities that pertain to the resonance frequencies that lie within $(\Delta\omega)$. In transiting from Equation (a) to (b) on Viewgraph (8), equipartion of modal energy is assumed; namely, $\mathcal{E}_{\alpha j} \simeq \mathcal{E}_{\alpha i} = \mathcal{E}_\alpha$ and $\mathcal{E}_{\gamma q} = \mathcal{E}_{\gamma r} = \mathcal{E}_\gamma$ of modes that lie within the modal span functions $U_{\alpha j}$ and $U_{\gamma q}$, respectively. Equation (c) on Viewgraph (8), merely generalized Eq. (b) and cast this generalization in matrix form. Note that $\bar{\eta}_{\gamma\alpha} = \bar{\eta}_{\alpha\gamma}$ but $\eta_{\gamma\alpha}$ is not necessarily equal to $\eta_{\alpha\gamma}$. Indeed, the two quantities; namely, $\eta_{\gamma\alpha}$ and $\eta_{\alpha\gamma}$, are related by a consistency relationship, as stated in Viewgraph (9).

14

Modal equation of SEA

$$\varepsilon_{\alpha j} \simeq M_\alpha |v_{\alpha j}|^2 \simeq 2\varepsilon_{K\alpha j}$$

$$\pi_{\alpha j} = \mathrm{Re}\{(v_{\alpha j})^* p_{e\alpha j}\}$$

$$\eta_{\alpha j \alpha j} = Re\{z_{\alpha j \alpha j}/(\omega M_\alpha)\}$$

Using the modal span functions $U_{\alpha j}(\omega, \omega_{\alpha j}, \eta_{\alpha j})$

$$\left\langle \eta_{\alpha j \alpha j}\varepsilon_{\alpha j} + \sum_\gamma \sum_q \eta_{\alpha j \gamma q}(\varepsilon_{\alpha j} - \varepsilon_{\gamma q})(1-\delta_{\alpha\gamma}) = (\pi_{e\alpha j}/\omega) \right\rangle_{\Delta\omega} , \qquad (a)$$

$$\eta_{\alpha\alpha}\varepsilon_\alpha + \sum_\gamma \eta_{\gamma\alpha}(\varepsilon_\alpha - \varepsilon_\gamma)(1-\delta_{\alpha\gamma}) = (\pi_{e\alpha}/\omega) , \qquad (b)$$

$$(\underset{\approx}{\eta}\,\underset{\approx}{\omega})\,\underset{\sim}{\varepsilon} = \underset{\sim}{\pi}_e ; \qquad \underset{\approx}{\eta} = (\eta_\alpha \delta_{\alpha\gamma} - \eta_{\gamma\alpha}(1-\delta_{\alpha\gamma})) . \qquad (c)$$

$$\underset{\approx}{\omega} = (\omega\delta_{\alpha\gamma}) ; \qquad \underset{\sim}{\varepsilon} = \{\varepsilon_\alpha\} \quad ; \qquad \underset{\sim}{\pi}_e = \{\pi_{e\alpha}\}$$

$$\eta_\alpha = \sum_\gamma \eta_{\gamma\alpha} ; \qquad \eta_{\gamma\alpha} = n_\gamma \overline{\eta}_{\gamma\alpha} ; \qquad \overline{\eta}_{\gamma\alpha} = \langle \eta_{\gamma q \alpha j} \rangle_{\Delta\omega}$$

Viewgraph 9

Global density quantities are defined in terms of the (typical) modal quantities and the modal densities. The modal density $n_\alpha(\omega)$ of the (α)th substructure counts the modes per unit frequency that reside about the frequency (ω). Thus, $n_\alpha(\omega)(\Delta\omega)$ are the number of modes that are spanned within the modal span function. This number is $\langle U_{\alpha j}(\omega, \omega_{\alpha j}, \eta_{\alpha j}\rangle_{\Delta\omega}$. [cf. Viewgraph (8).] As indicated on the figure, a substructure at SEA is completely defined in terms of its loss factor; e.g., $(\eta_{\alpha\alpha})$ for the (α)th substructure, of its modal density; e.g., (n_α) for the (α)th substructure, of its mass; e.g., (M_α) for the (α)th substructure* and, finally, of its coupling loss factors; e.g., $\eta_{\alpha\gamma}$ for the coupling between the (γ)th and the (α)th substructures. Consistent relationships exist among the coupling loss factors as stated in Viewgraph (9).

* The mass of a substructure, (M_α) for the (α)th substructure, is seldom stated explicitly, but is always implied.
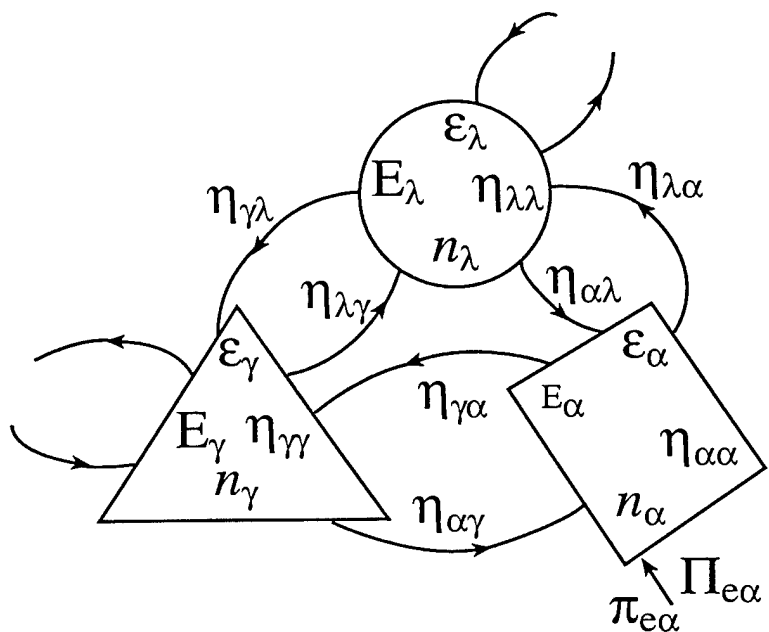
$$E_\alpha = n_\alpha \varepsilon_\alpha \qquad \text{Stored Energy Density}$$

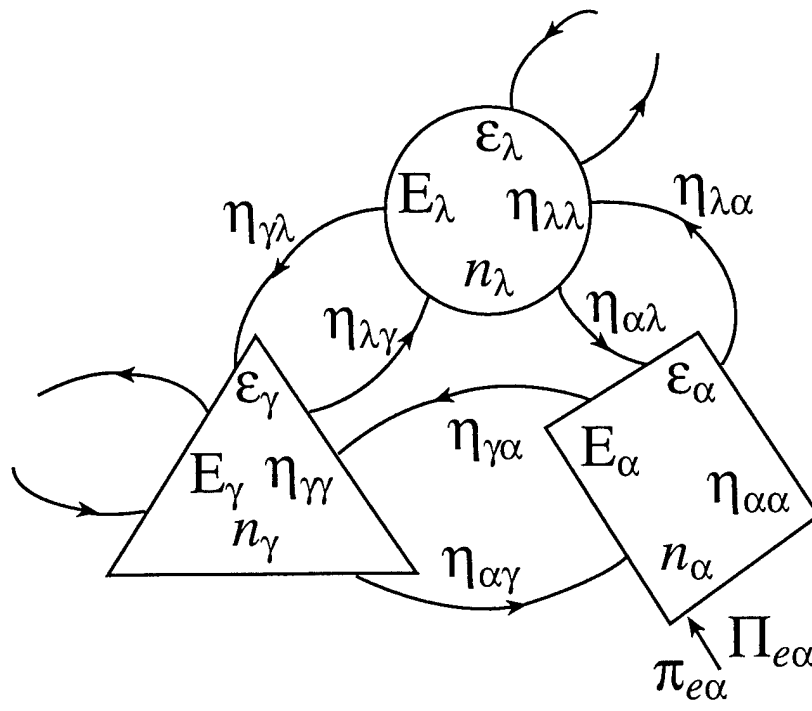$$\Pi_{e\alpha} = n_\alpha \pi_{e\alpha} \qquad \text{Input Power (External)}$$
Density

$$(\eta_{\gamma\alpha} / \eta_{\alpha\gamma}) = (n_\gamma / n_\alpha) \qquad \text{Consistency Relationship}$$

Viewgraph 10

       In Viewgraph (10) a statement of the matrix modal equation of motion and the

matrix global equation of motion at SEA are stated. Note the difference between the loss

factor matrix $\underset{\approx}{\eta}$ for the modal and the global equations. The difference lies merely in the

off-diagonal elements and that difference is accounted for by the consistency relationship

stated in Viewgraph (9). The matrices are the transpose of each other.

Modal SEA

$$\underset{\approx}{\eta} \; \underset{\approx}{\omega} \; \underset{\sim}{\varepsilon} = \underset{\sim}{\pi}_e \quad ; \quad \underset{\sim}{\varepsilon} = \{\varepsilon_\alpha\} \quad ; \quad \underset{\sim}{\pi}_e = \{\pi_{e\alpha}\} \quad ;$$

$$\underset{\approx}{\eta} = \left(\eta_\alpha \delta_{\alpha\gamma} - \eta_{\gamma\alpha}(1-\delta_{\alpha\gamma})\right) \quad ; \quad \eta_\alpha = \sum_\gamma \eta_{\gamma\alpha} \quad ;$$

Global SEA

$$\underset{\approx}{\eta} \; \underset{\approx}{\omega} \; \underset{\sim}{E} = \underset{\sim}{\Pi}_e \quad ; \quad \underset{\sim}{E} = \{E_\alpha\} \quad ; \quad \underset{\sim}{\Pi}_e = \{\Pi_{e\alpha}\} \quad ;$$

$$\underset{\approx}{\eta} = \left(\eta_\alpha \delta_{\alpha\gamma} - \eta_{\alpha\gamma}(1-\delta_{\alpha\gamma})\right) \quad , \quad \underset{\approx}{\omega} = \left(\omega \delta_{\alpha\gamma}\right) \quad .$$
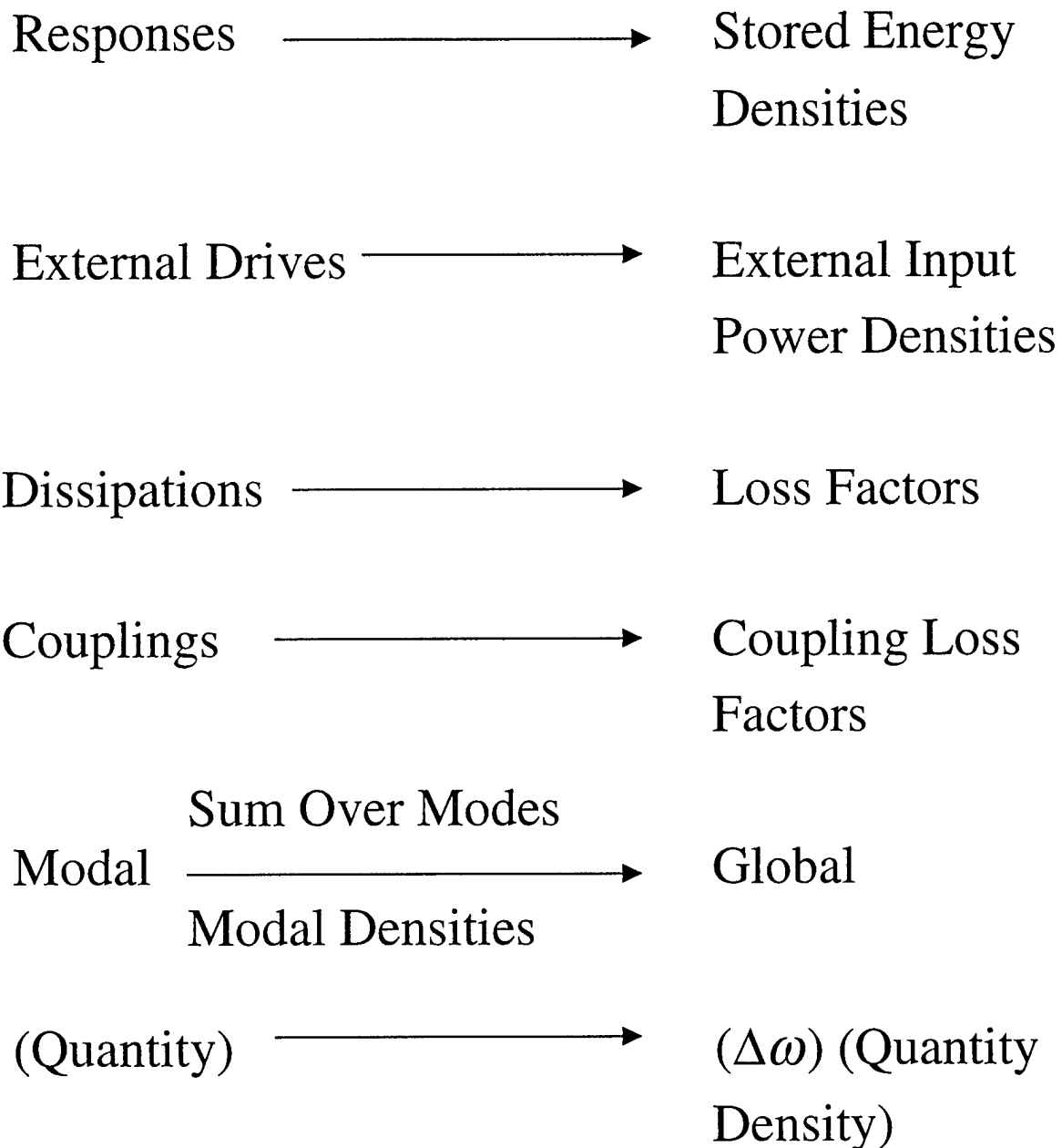
Viewgraph 11

A recap is briefly stated in Viewgraph (11).

The spatial dependence in the equation of motion is removed by introducing sets of orthogonal modes: A set of modes per substructure.

The phase dependence is removed by quadratizing linear quantities:

Responses $\longrightarrow$ Stored Energy Densities

External Drives $\longrightarrow$ External Input Power Densities

Dissipations $\longrightarrow$ Loss Factors

Couplings $\longrightarrow$ Coupling Loss Factors

Modal $\xrightarrow{\text{Sum Over Modes}}$ Global

Modal Densities

(Quantity) $\longrightarrow$ $(\Delta\omega)$ (Quantity Density)
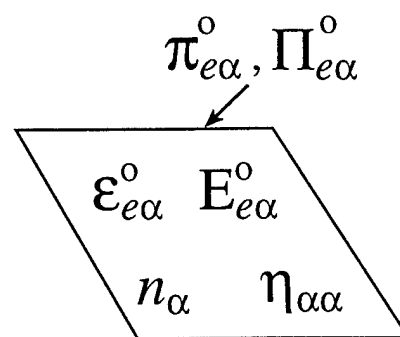
Viewgraph 12

A question may be asked as to whether the external input power density into a substructure; e.g., the (α) th substructure, is affected by the couplings to other substructures. When SEA was developing under the assumption that the coupling strengths are weak; e.g.,

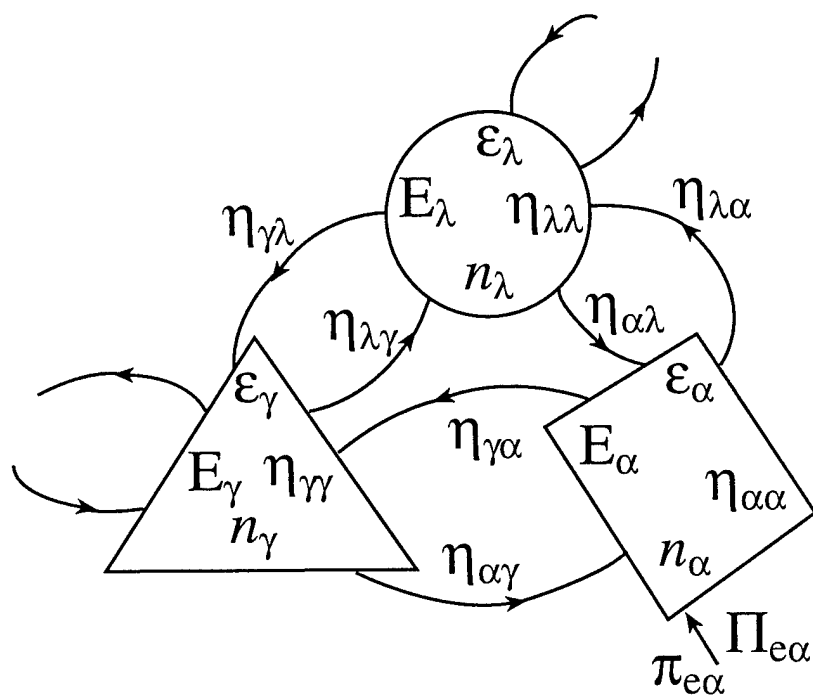$$\eta_{\alpha\gamma}(\eta_{\gamma\gamma} + \eta_{\alpha\gamma})^{-1} \ll 1 \quad,$$

the external input power density (Π_α) into the (α) th substructure was assumed to be unaffected by the couplings; i.e., it was assumed that

$$(\Pi_{e\alpha} / \Pi_{e\alpha}^o) \equiv 1 \quad.$$

Is this result valid for coupling strengths that are strong? A heuristic argument is developed in an attempt to answer this question.

$$\pi^o_{e\alpha}, \Pi^o_{e\alpha}$$

$$\varepsilon^o_{e\alpha} \quad E^o_{e\alpha}$$

$$n_\alpha \qquad \eta_{\alpha\alpha}$$

$$\Pi_{e\alpha} / \Pi^o_{e\alpha} = ?$$

$$\varepsilon_\lambda$$
$$E_\lambda \quad \eta_{\lambda\lambda}$$
$$n_\lambda$$

$$\eta_{\gamma\lambda} \qquad \eta_{\lambda\alpha}$$

$$\eta_{\lambda\gamma} \qquad \eta_{\alpha\lambda}$$

$$\varepsilon_\gamma$$
$$E_\gamma \quad \eta_{\gamma\gamma}$$
$$n_\gamma$$

$$\eta_{\gamma\alpha}$$

$$\varepsilon_\alpha$$
$$E_\alpha \qquad \eta_{\alpha\alpha}$$
$$n_\alpha$$

$$\eta_{\alpha\gamma}$$

$$\pi_{e\alpha} \qquad \Pi_{e\alpha}$$

Viewgraph 13

For this purpose it is found useful to first define a modal coupling strength (ξ_α^γ) and its counterpart, a global coupling strength (Ξ_α^γ). The definitions are cast in proper parametric forms; the modal and the global coupling strengths, (ξ_α^γ) and (Ξ_α^γ), respectively, are functional of only those parameters that describe the substructures and the couplings between them. These parametric forms are not functional of the external input power into and/or the stored energies in the substructures. Also, note the natural upper limits on the modal and the global coupling strengths.
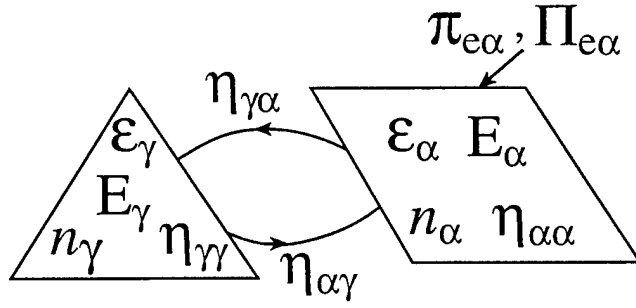
It is convenient to define the coupling between the

$(\gamma)\,th$ and the $(\alpha)th$ substructures in terms of a modal

coupling strength. This modal coupling strength is
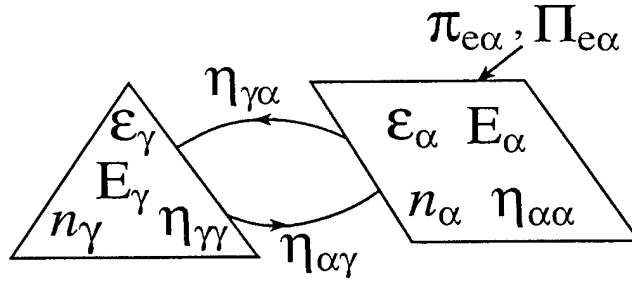
designated (ξ_α^γ) and its expression is:

$$(\varepsilon_\gamma / \varepsilon_\alpha) = \eta_{\alpha\gamma}(\eta_{\gamma\gamma} + \eta_{\alpha\gamma})^{-1} = \xi_\alpha^\gamma < 1 \quad .$$

Global coupling strength

$$(E_\gamma / E_\alpha) = (n_\gamma / n_\alpha)\xi_\alpha^\gamma = \Xi_\alpha^\gamma < (n_\gamma / n_\alpha) \quad .$$

Viewgraph 14

The definitions of the modal and the global coupling strengths are repeated and

the notion of weak and strong couplings are explicitly stated.

Modal coupling strength

$$(\varepsilon_\gamma / \varepsilon_\alpha) = \eta_{\alpha\gamma}(\eta_{\gamma\gamma} + \eta_{\alpha\gamma})^{-1} = \xi_{\gtrless\alpha}^\gamma < 1 \quad .$$

Global coupling strength

$$(E_\gamma / E_\alpha) = (n_\gamma / n_\alpha)\xi_{\gtrless\alpha}^\gamma = \Xi_\alpha^\gamma < (n_\gamma / n_\alpha) \quad .$$

Weak coupling:

$$\left.\begin{cases} \xi_{\gtrless\alpha}^\gamma << 1 \\ \Xi_\alpha^\gamma << (n_\gamma / n_\alpha) \end{cases}\right\} \quad ; \quad \text{i.e.,} \quad \eta_{\gamma\gamma} >> \eta_{\alpha\gamma} \quad ,$$

Strong coupling:

$$\left.\begin{cases} \xi_{\gtrless\alpha}^\gamma \lesssim 1 \\ \Xi_\alpha^\gamma \lesssim (n_\gamma / n_\alpha) \end{cases}\right\} \quad ; \quad \text{i.e.,} \quad \eta_{\gamma\gamma} \lesssim \eta_{\alpha\gamma} \quad .$$

Viewgraph 15

The definition for the external input power density, into an isolated substructure, in terms of the spectral density of the external drive and the conductance is standard. The expression for the conductance in terms of the modal density and the mass of a substructure is also standard. Relying on these standards, the conductance of a coupled substructure is heuristically suggested. Of course, the couplings may alter the modal densities as well as the masses that define the substructure. It is assumed that such alterations are second order effects even when the coupling are strong; i.e., it is assumed that the n_α's and M_α's are robust parameters with respect to couplings. Under this assumption typically the ratio $(G_\alpha\ /\ G_\alpha^o)$ may be determined as stated.
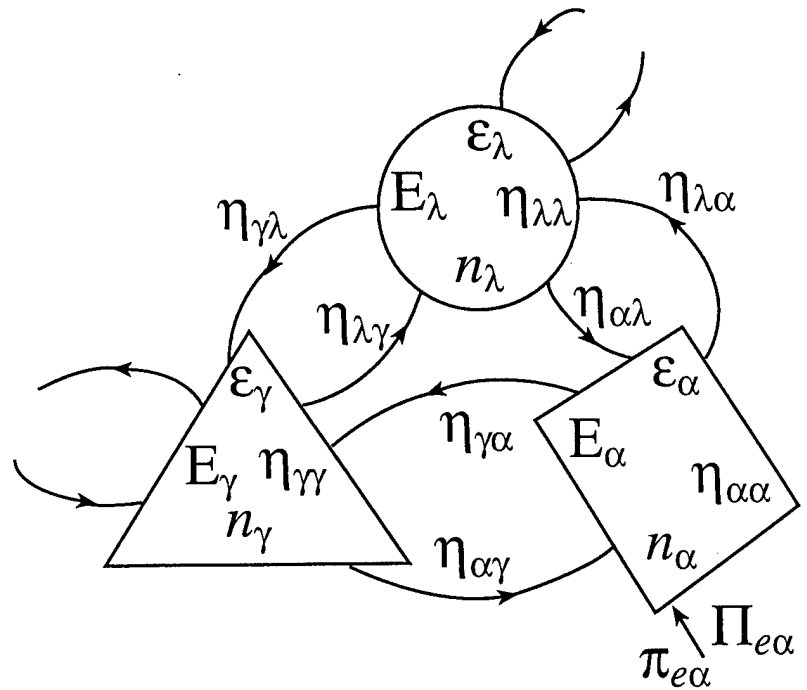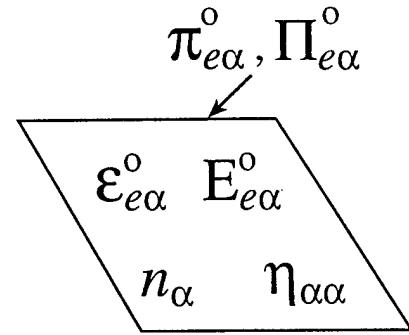
External Input Power

$$G^o_\alpha S_{f\alpha} = \Pi^o_{e\alpha} \quad ,$$

$$G^o_\alpha = (\pi/2)(n_\alpha/M_\alpha) \quad ,$$

$$G_\alpha S_{f\alpha} = \Pi_{e\alpha},$$

$$G_\alpha = (\pi/2)(n'_\alpha/M'_\alpha) \quad ,$$

$$\Pi_{e\alpha}/\Pi^o_{e\alpha} = (G_\alpha/G^o_\alpha) \ ?$$

$$n'_\alpha = [n_\alpha + \sum_{\gamma \neq \alpha}(n_\gamma \zeta^\gamma_\alpha)] \ ; \ M'_\alpha = [M_\alpha + \sum_{\gamma \neq \alpha} M_\gamma \zeta^\gamma_\alpha]$$

$$(G_\alpha/G^o_\alpha) = [1 + \sum_{\gamma \neq \alpha}(\Xi^\gamma_\alpha)][1 + \sum_{\gamma \neq \alpha}(M_\gamma/M_\alpha)\zeta^\gamma_\alpha]^{-1} \quad .$$

Viewgraph 16

Modifications to the global equation of motion at SEA are, thus, suggested so that the equation may be expressed in terms of the external input power density vector $\underset{\sim}{\Pi}_e$ or in terms of the external input power density vector $\underset{\sim}{\Pi}_e^o$. The latter input power density is determined when the couplings are removed. How significant is this modification to SEA? Before answering this question, two simple examples in which the modification is insignificant are considered for the record.

In the first, weak coupling is assumed. For this case, weak coupling is defined as

$$\left(\sum_{\gamma \neq \alpha} \Xi_\alpha^\gamma \right) \ll 1 \text{ and } \left[\sum_{\gamma \neq \alpha} (M_\gamma / M_\alpha) \xi_\alpha^\gamma \right] \ll 1 \ .$$

Under this definition $\underset{\approx}{R} = \underset{\approx}{1}$.

$$(G_\alpha / G_\alpha^o) = [1+\sum_{\gamma \neq \alpha} \Xi_\alpha^\gamma][1+\sum_{\gamma \neq 2}(\overline{m}_\gamma / \overline{m}_\alpha)\Xi_\alpha^\gamma]^{-1}; \quad \overline{m}_\gamma = (M_\gamma / n_\gamma$$

$$(G_\alpha / G_\alpha^o) = \begin{cases} > 1 \; ; \; \text{modal density}-\text{rich couplings} \\ 1 \; ; \; \text{similar couplings} \\ < 1 \; ; \; \text{mass}-\text{rich couplings} \end{cases}$$

$$\underset{\approx}{\beta}\underset{\sim}{E} = (\underset{\approx}{\eta}\underset{\approx}{\omega})\underset{\sim}{E} = \underset{\sim}{\Pi}_e = \underset{\approx}{R}\underset{\sim}{\Pi}_e^o$$

$$(\underset{\sim}{\Pi}_e / \underset{\sim}{\Pi}_e^o) = (G_\alpha / G_\alpha^o)$$

$$G_\alpha^o S_{f\alpha} = \Pi_{e\alpha}^o \quad ; \quad G_\alpha S_{f\alpha} = \Pi_{e\alpha}$$

$$\underset{\approx}{R} = (R_\alpha \delta_{\alpha\gamma}) \quad ; \quad R_\alpha = [1+\sum_{\gamma \neq \alpha} \Xi_\alpha^\gamma]\frac{[1+\sum_{\gamma \neq \alpha}(\overline{m}_\gamma / \overline{m}_\alpha)\Xi_\alpha^\gamma]^{-1}}{[1+\sum_{\gamma \neq \alpha}(M_\gamma / M_\alpha)\xi_\alpha^\gamma]^{-1}}$$

In the second, similar coupling is assumed. In this case

$$(M_\alpha / n_\alpha) = (M_\gamma / n_\gamma) = (M / n) = \overline{m}$$

and, therefore, again $\underset{\approx}{R} = \underset{\approx}{1}$. A physical structure that trivially falls into this category

is derived by introducing a "control line" on a plate; the control line is featured by the

dashed line. In this example $n_\lambda \propto A_\lambda$; $M_\lambda \propto A_\lambda$ and $\xi_\alpha^\gamma \to 1$. Therefore, similar

couplings are assured and $(\Pi_{e\alpha} / \Pi_{e\alpha}^o) = 1$. A ratio that may be of interest to

determine is (E_α / E_α^o). The determination is presented in Viewgraph (17). The results

indeed make physical sense and could be apriori predicted.

$S_{f\alpha}$

E_α^o M_α

n_α

$\eta_{\alpha\alpha}$

$S_{f\alpha}$

E_α M_α

n_α

E_γ

$\eta_{\alpha\alpha}$

n_γ $\eta_{\gamma\gamma}$

M_γ
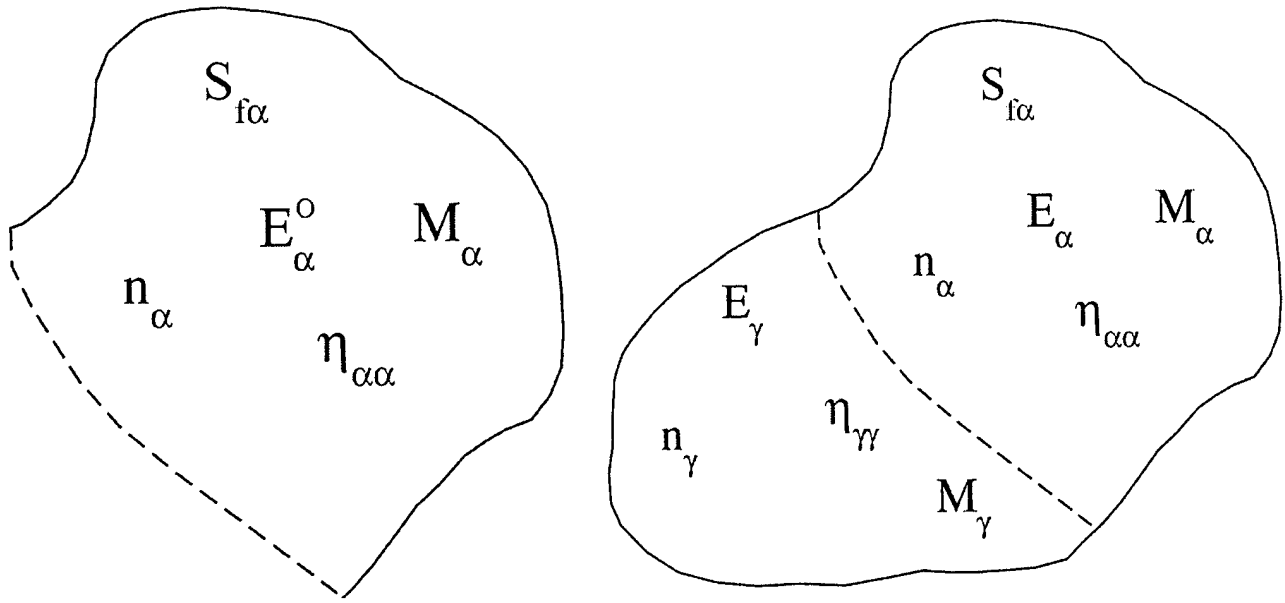
$$n_\lambda \propto A_\lambda \quad ; \quad M_\lambda \propto A_\lambda \quad \text{and} \quad \xi_\alpha^\gamma \to 1$$

$$\therefore \text{ Similar couplings and } (\Pi_{e\alpha} / \Pi_{e\alpha}^o) \to 1$$

$$(E_\alpha / E_\alpha^o) = (\eta_{\alpha\alpha} / \eta_t) \quad ; \eta_t = [\eta_{\alpha\alpha} + \eta_{\gamma\gamma}(A_\gamma / A_\alpha)]$$

$$(E_\alpha / E_\alpha^o) = (A_\alpha / A)(\eta_{\alpha\alpha} / \eta_e) \quad ; A = A_\alpha + A_\gamma$$

$$\eta_e = (A)^{-1} [\eta_{\alpha\alpha} A_\alpha + \eta_{\gamma\gamma} A_\gamma]$$

$$(E_\alpha / E_\alpha^o) \simeq \frac{\Pi_{\text{diss}}}{\text{in } (\alpha)\text{th}} \Big/ \frac{\Pi_{\text{diss}}}{\text{in } [(\alpha)\text{th} + (\gamma)\text{th}]}$$

$$\text{If } \eta_{\alpha\alpha} \simeq \eta_{\gamma\gamma} \quad , \quad (E_\alpha / E_\alpha^o) \simeq (A_\alpha / A)$$
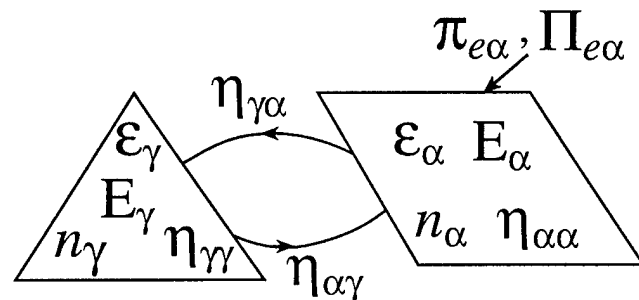
Viewgraph 18

What is the relevance of the modified global equation of motion at SEA to its

application, say, to a noise control problem? The application is illustrated in

Viewgraph 18. In this viewgraph, a substructure; e.g., the (α) th is depicted in isolation

and as coupled to another substructure; e.g., the (γ) th. The coupling is introduced in

order to achieve a noise control goal, as stated in Viewgraph 18. A generic definition of

a loss factor is suggested and challenged.

A noise control goal is usually expressed in SEA by a ratio of quantities. Thus, a legitimate noise control goal may be expressed in terms of minimizing (E_α / E_α^o).

$$\pi_{e\alpha}^o, \Pi_{e\alpha}^o$$

$$\varepsilon_{e\alpha}^o \quad E_{e\alpha}^o$$

$$n_\alpha \quad \eta_{\alpha\alpha}$$
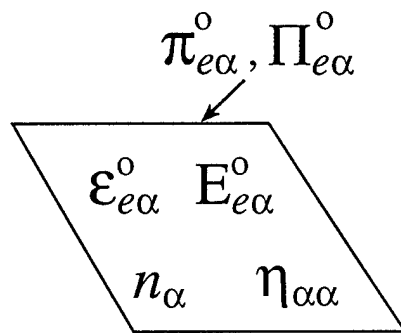
Isolated
(Uncoupled)

Coupled

$$\pi_{e\alpha}, \Pi_{e\alpha}$$

$$\eta_{\gamma\alpha}$$

$$\varepsilon_\gamma$$
$$E_\gamma$$
$$n_\gamma \quad \eta_{\gamma\gamma}$$

$$\varepsilon_\alpha \quad E_\alpha$$
$$n_\alpha \quad \eta_{\alpha\alpha}$$

$$\eta_{\alpha\gamma}$$

Some of these ratios are defined as loss factors, i.e.,

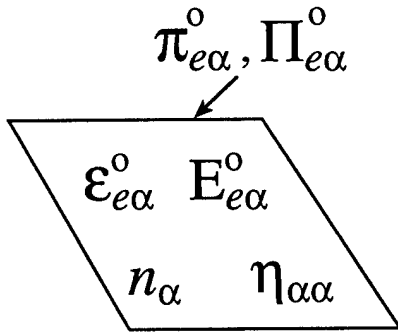$$\eta = [\Pi_e / (\omega E)] \quad ; \qquad \text{What } \Pi_e ?$$

What E ?

Viewgraph 19

The generic definition for a loss factor may support a number of definitions. The relationships among these definitions are also presented. All these definitions pertain to loss factors that are of proper parametric forms. Which of these definitions address true loss factors is also noted.
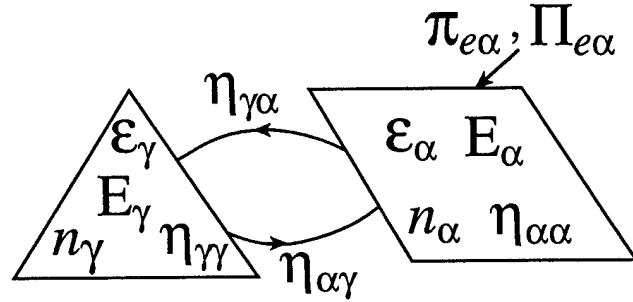
A loss factor requires accounting for the external input power density into a structure (or a substructure) and the generated energy density stored in the structure needs to be totally accounted for. Otherwise, questions such as "Where did the energy go?" may arise in a formalism that is basically a statement of the "conservation of energy."

$\pi^{o}_{e\alpha}, \Pi^{o}_{e\alpha}$

$\varepsilon^{o}_{e\alpha} \quad E^{o}_{e\alpha}$

$n_{\alpha} \quad \eta_{\alpha\alpha}$

Coupled

Isolated
(Uncoupled)

$\eta_{\gamma\alpha}$

ε_{γ}

E_{γ}

$n_{\gamma} \quad \eta_{\gamma\gamma}$

$\eta_{\alpha\gamma}$

$\pi_{e\alpha}, \Pi_{e\alpha}$

$\varepsilon_{\alpha} \quad E_{\alpha}$

$n_{\alpha} \quad \eta_{\alpha\alpha}$

$$\eta_{\alpha\alpha} = [\Pi^{o}_{e}/(\omega E^{o}_{\alpha}) \quad ; \quad \eta^{\alpha}_{t\alpha} \equiv \eta_{t} = [\Pi_{e\alpha}/(\omega E_{\alpha})] \quad ;$$

$$\eta^{\alpha}_{t\gamma} \equiv \eta_{t\gamma} = [\Pi_{e\alpha}/(\omega E_{\gamma})] \quad ; \quad \eta^{\alpha}_{e} \equiv \eta_{e} = [\Pi_{e\alpha}/(\omega E)] \quad ;$$

$$E = (E_{\alpha} + E_{\gamma}) \quad ; \quad \Pi_{e\alpha} = \omega[(\eta_{\alpha\alpha}E_{\alpha}) + (\eta_{\gamma\gamma}E_{\gamma})] \quad .$$
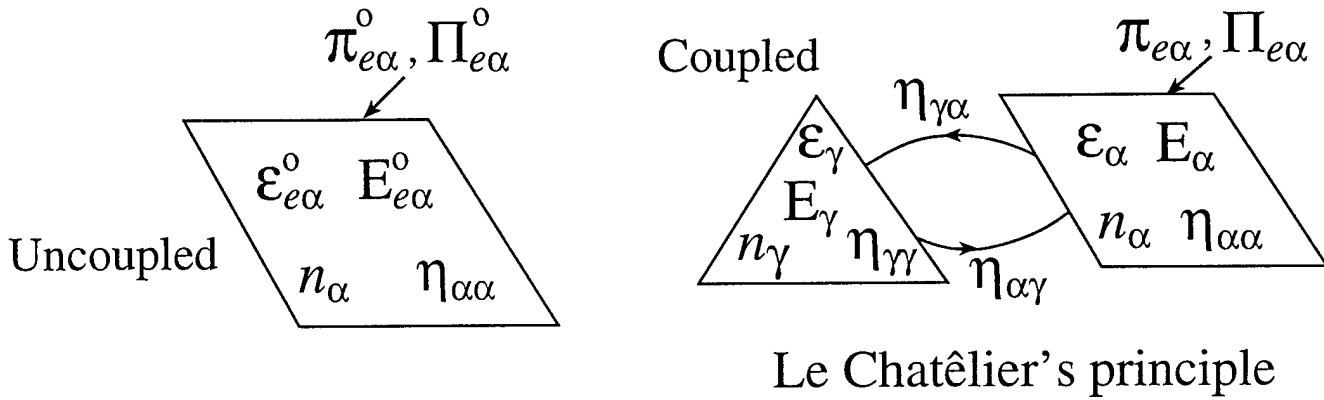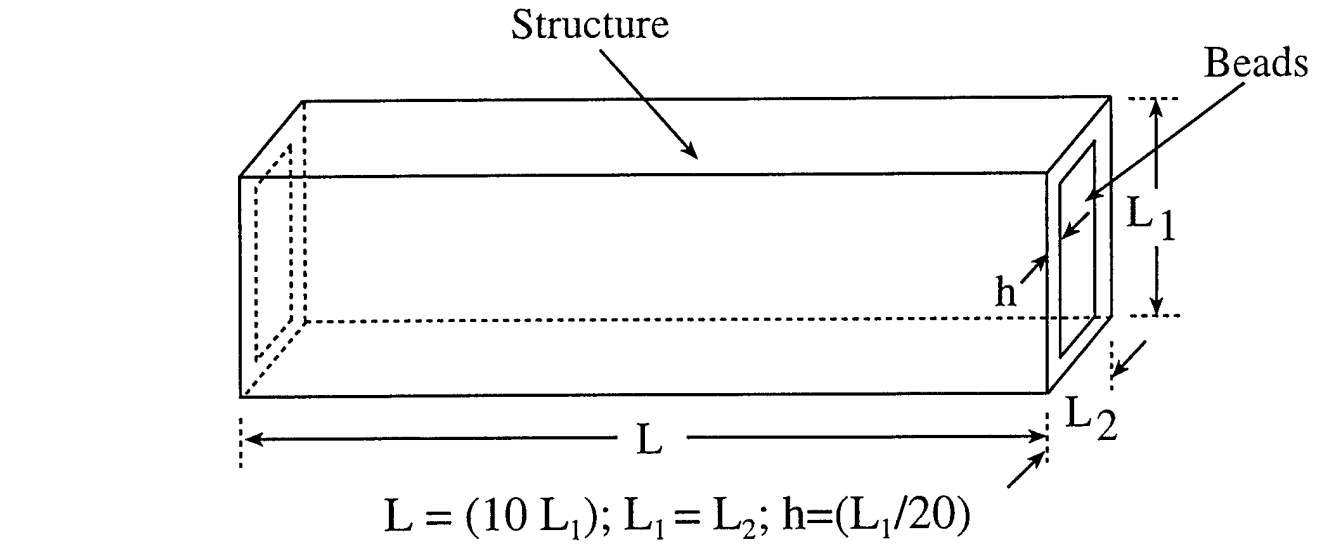
$$\eta_{t} = [\eta_{\alpha\alpha} + \eta_{\gamma\gamma}\Xi^{\gamma}_{\alpha})] \quad ; \quad \eta_{t\gamma} = \eta_{t}(\Xi^{\gamma}_{\alpha})^{-1} \quad ;$$

$$\eta_{e} = \eta_{t}[1 + \Xi^{\gamma}_{\alpha})]^{-1} \quad ; \quad \Xi^{\gamma}_{\alpha} = (E_{\gamma}/E_{\alpha}) \quad .$$

Only $\eta_{\alpha\alpha}$, $\eta_{\gamma\gamma}$, and η_{e} are TRUE loss factors.

V.19

37

Viewgraph 20

A practical example is presented in Viewgraph 20. A hollow rectangular steel structure is considered as a master substructure. This substructure is coupled to another. The second substructure is composed of beads that fill-in the hollow space. The beads are modeled as a fluid of low compressibility compared with that of *water* and density that is comparable with that of *water*. The low compressibility and the moderate density yield a low sound speed; e.g., in the range of one-fifth of the sound speed in *air*. The low speed of sound generates high modal densities. The rubbing of beads against their neighbors yield high loss factors in the beaded-fluid. The moderate density allows, nonetheless, for reasonably high coupling strengths. These attributes qualify the beaded-fluid substructure as a structural fuzzy. As such, in the steady state condition, a significant portion of the energy density is stored in the adjunct structure and much of it is efficiently dissipated. In this way the structural fuzzy constitutes an effective damping device; however, at best it yields an overall loss factor that converges on that of the adjunct substructure, as dictated by Le Chatelier's Principle. Le Chatelier's Principle roughly states: "When a dynamic system is modified (e.g., by coupling to it a structural fuzzy) with the intention of achieving a high degree of change in the noise it issues, the achievement is mitigated by the implementation of the modification," e.g., the loss factor converges, at best, to that of the adjunct substructure.

Structure

Beads

L_1

h

L_2

L

$L = (10\,L_1); \; L_1 = L_2; \; h = (L_1/20)$

$\pi^o_{e\alpha}, \Pi^o_{e\alpha}$

Coupled

$\pi_{e\alpha}, \Pi_{e\alpha}$

$\varepsilon^o_{e\alpha} \quad E^o_{e\alpha}$

$n_\alpha \quad \eta_{\alpha\alpha}$

Uncoupled

$\eta_{\gamma\alpha}$

ε_γ

E_γ

$n_\gamma \quad \eta_{\gamma\gamma}$

$\eta_{\alpha\gamma}$

$\varepsilon_\alpha \quad E_\alpha$

$n_\alpha \quad \eta_{\alpha\alpha}$

Le Chatêlier's principle

$$(E_\alpha / E^o_\alpha) = (\Pi_{e\alpha} / \Pi^o_{e\alpha})\,(\eta_{\alpha\alpha}/\eta_t)$$

$$\eta_t = [(\eta_{\alpha\alpha} + (\eta_{\gamma\gamma}\Xi^\gamma_\alpha)] \quad ; \quad (\Pi_{e\alpha}/\Pi^o_{e\alpha}) \overset{?}{=} 1$$

$$(\Pi_{e\alpha}/\Pi^o_{e\alpha}) = (1 + \Xi^\gamma_\alpha)\,[1 + (\overline{m}_\gamma/\overline{m}_\alpha)\Xi^\gamma_\alpha]^{-1}$$

$$(E_\alpha/E^o_\alpha) = (\eta_{\alpha\alpha}/\eta_e)\,[1 + (\overline{m}_\gamma/\overline{m}_\alpha)\Xi^\gamma_\alpha]^{-1}$$

$$\eta_e = [(\eta_{\alpha\alpha} + \eta_{\gamma\gamma}\Xi^\gamma_\alpha)[1 + \Xi^\gamma_\alpha]^{-1}$$

V.20

39

Viewgraph 21

The attributes of the combined structure, comprising the master substructure and the adjunct substructure, are exemplified in Viewgraph 21 a and b. The loss factor η_t, in Viewgraph 21c, is that derived by setting the ratio $(\Pi_{e\alpha} / \Pi_{e\alpha}^{o})$ equal to unity. [cf. Viewgraph 20.] The convergence of the overall loss factor onto η_e is clearly discernable in Viewgraph 21.

Standard Structure
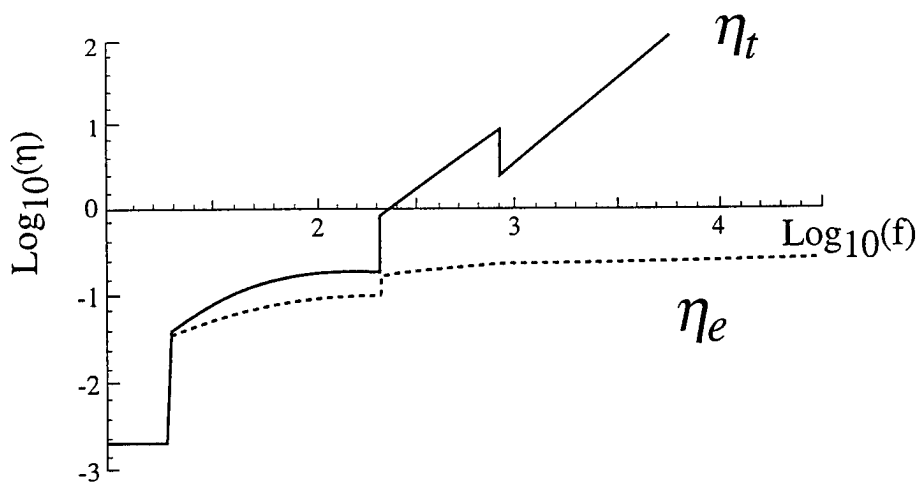
$$L = (10 L_1); \quad L_1 = L_2; \quad h = (L_1 / 20)$$
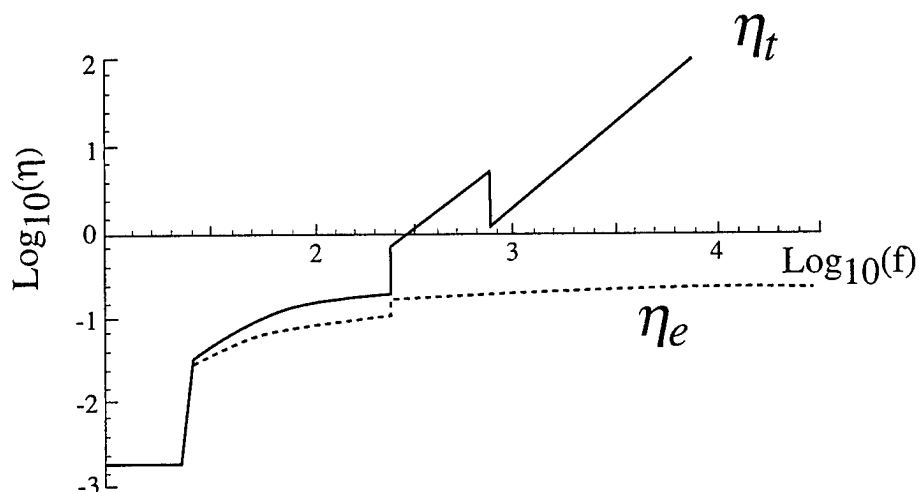

a)

b)

c)
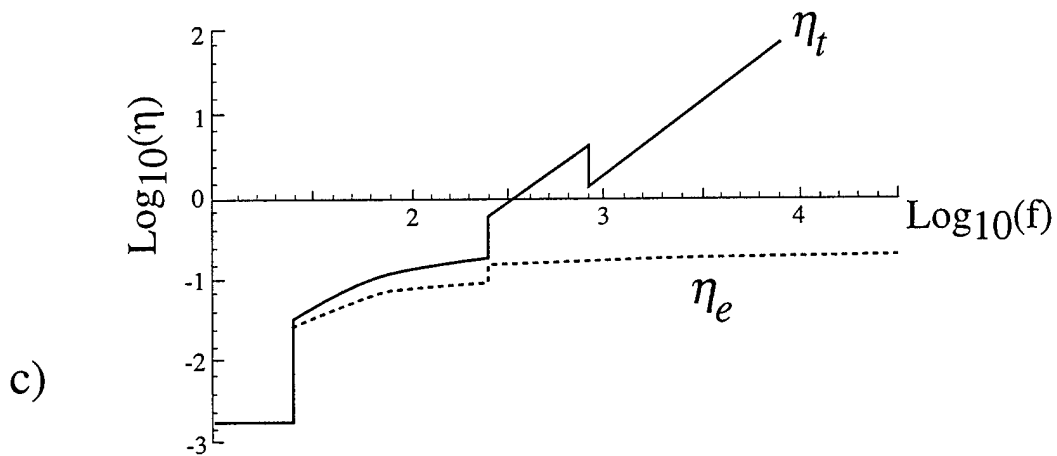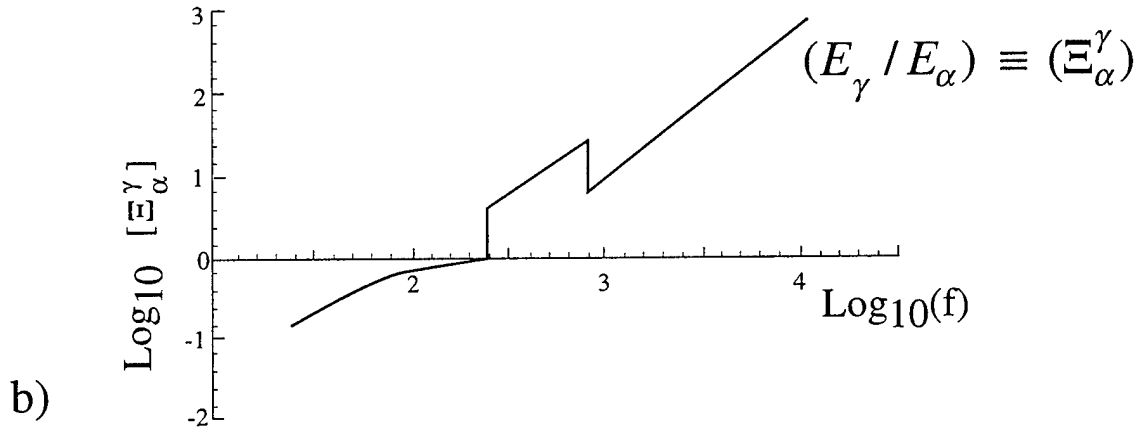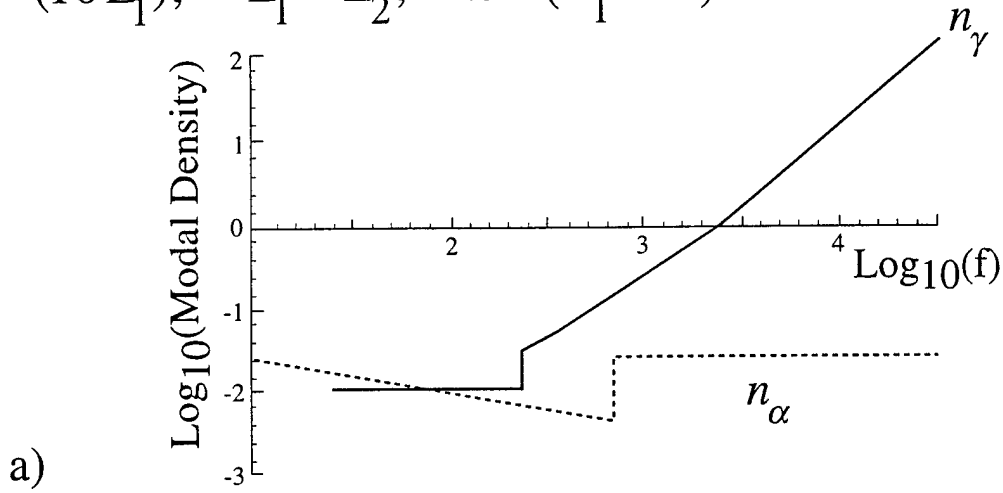
Standard Beads

$$c_\gamma = 250; \quad (\rho_\alpha / \rho_\gamma) = 10; \quad \eta_{\alpha\alpha} = 0.002; \quad \eta_{\gamma\gamma} = 0.2$$
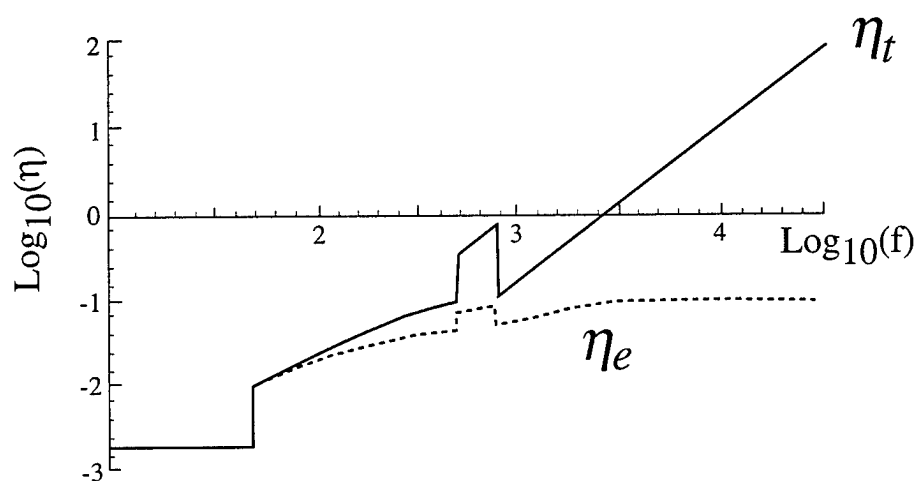
Viewgraph 22

Variations on the standard theme are depicted in this Viewgraph; polybeads and beads in the form of sand are exemplified. Again, differentiation between η_t and η_e is illustrated. The convergence of the loss factor η_e on the loss factor $\eta_{\gamma\gamma}$, of the structural fuzzy, is of particular interest.

Poly Beads: $c_\gamma = 200$, $(\rho_\alpha / \rho_\gamma) = 12$, $\eta_{\alpha\alpha} = 0.002$, $\eta_{\gamma\gamma} = 0.2$

Standard: $c_\gamma = 250$, $(\rho_\alpha / \rho_\gamma) = 10$, $\eta_{\alpha\alpha} = 0.02$, $\eta_{\gamma\gamma} = 0.2$

Sand: $c_\gamma = 500$, $(\rho_\alpha / \rho_\gamma) = 4$, $\eta_{\alpha\alpha} = 0.002$, $\eta_{\gamma\gamma} = 0.1$
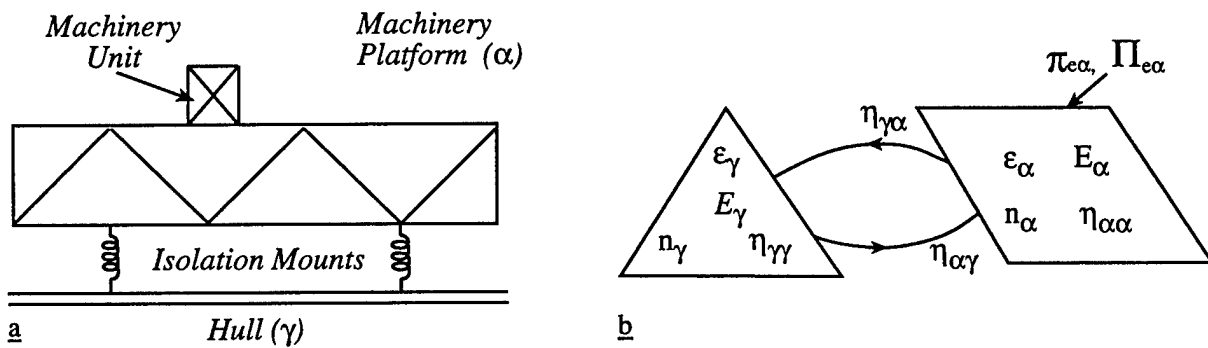
V.22

43

Viewgraph 23

In this Viewgraph the Principle of Supplementarity of Damping and Isolation is

annunciated and formulated. This example is the antonym of that of Structural Fuzzy.

Another noise control goal may be cast in terms of minimizing the ratio of the power density $[(\omega\eta_{\gamma\gamma})E_{\gamma}]$ dissipated in the passive $(\gamma)th$ substructure to the external input power density $(\Pi_{e\alpha})$ into the externally driven $(\alpha)th$ substructure: Example of the Principle of Supplementarity of Damping and Isolation.

$$\omega[(\eta_{\gamma\gamma}E_{\gamma}) + \eta_{\alpha\alpha}E_{\alpha}] = \Pi_{e\alpha} \quad ; \quad E = (E_{\alpha}+E_{\gamma})$$

$$\underbrace{[(\omega\eta_{\gamma\gamma}E_{\gamma})/\Pi_{e\alpha}]} = \Xi^{\gamma}_{\alpha}[(\eta_{\alpha\alpha}/\eta_{\gamma\gamma})+\Xi^{\gamma}_{\alpha}]^{-1} \; ; \; \Xi^{\gamma}_{\alpha} = (E_{\gamma}/E_{\alpha})$$
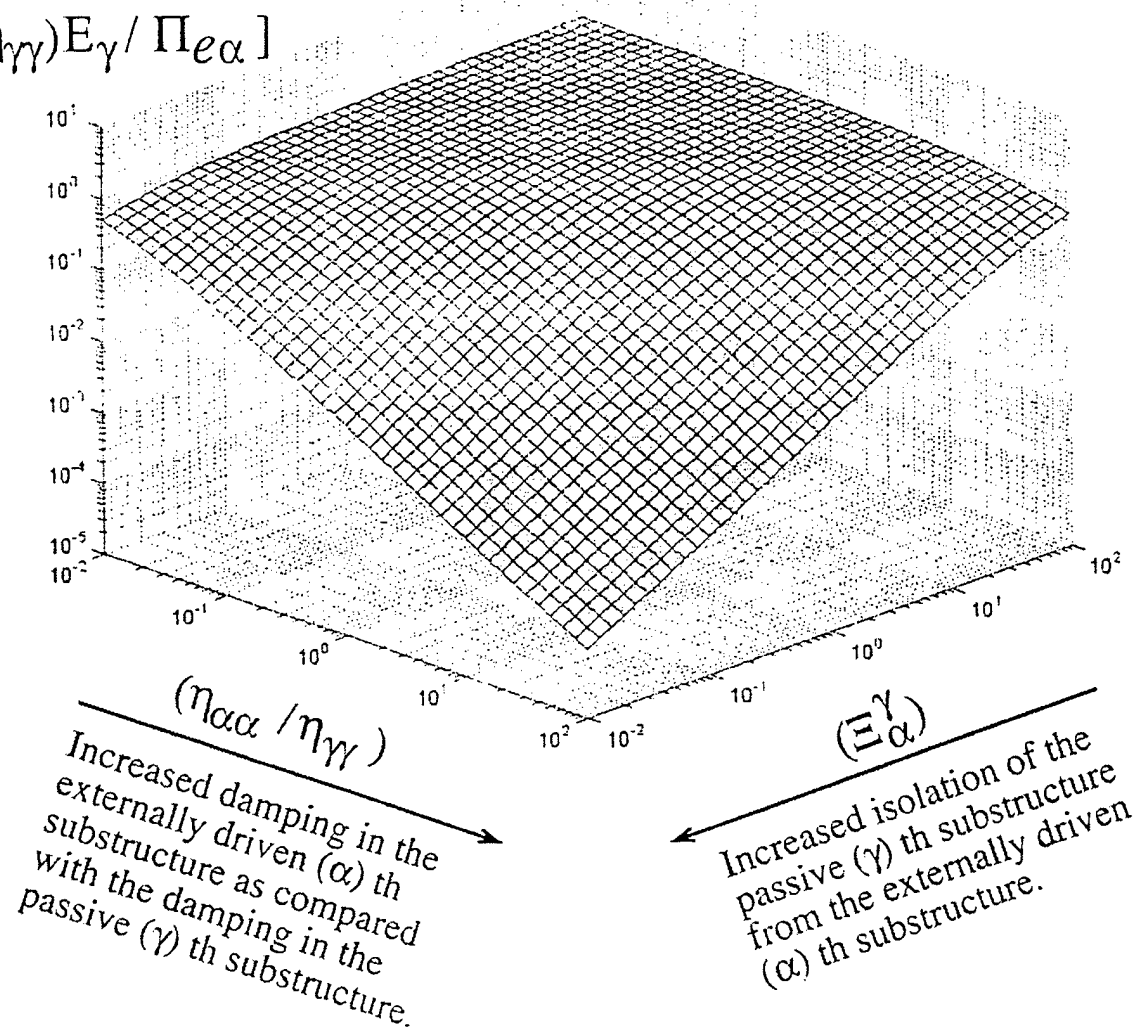
To be minimized

$\therefore$ Increase $(\eta_{\alpha\alpha}/\eta_{\gamma\gamma})$ and decrease Ξ^{γ}_{α}

Principle of Supplementarity of Damping and Isolation

Viewgraph 24.

In this Viewgraph the Principle of Supplementarity of Damping and Isolation is exemplified and illustrated.

$[(\omega\eta_{\gamma\gamma})E_\gamma / \Pi_{e\alpha}]$

$(\eta_{\alpha\alpha} / \eta_{\gamma\gamma})$

Increased damping in the externally driven (α) th substructure as compared with the damping in the passive (γ) th substructure.

(Ξ_α^γ)

Increased isolation of the passive (γ) th substructure from the externally driven (α) th substructure.

REFERENCES

1. R. H. Lyon, *Statistical Energy Analysis of Dynamic Systems: Theory and Applications* (MIT, Cambridge, 1975), and R. H. Lyon and R. G. Delong, *Theory and Application of Statistical Energy Analysis* (Butterworth-Heinemann, Boston, 1995).

2. K. L. Chandiramani, "Some simple models describing the transition from weak to strong coupling in statistical energy analysis," J. Acoust. Soc. Am. **63**, 1081-1083 (1978), and P. W Smith, Jr., "Statistical models of coupled dynamic systems and transition from weak to strong coupling," J. Acoust. Soc. Am., **64**, 695-698 (1979).

3. G. Maidanik and J. Dickey, "On the external input power into coupled structures," Proceedings of the Symposium of Statistical Energy Analysis, IUTAM, Southampton, England (1997).

INITIAL DISTRIBUTION

Copies

2 NAVSEA 05T2
  1   Taddeo
  1   Biancardi

5 ONR/ONT
  1   334   Tucker
  1   334   Radlinski
  1   334   Vogelsong
  1   334   Main
  1   Library

4 NRL
  1   5130 Bucaro
  1   5130 Williams
  1   5130 Photiadis
  1   Library

4 NUWC/NPT
  1   Sandman
  1   Harari
  1   3332 Lee
  1   Library

2 DTIC

2 Johns Hopkins University
  1   Green
  1   Dickey

2 ARL/Penn State University
  1   Burroughs
  1   Hwang

1 R.H. Lyons
  1   Lyons

1 Cambridge Collaborative
  1   Manning

1 Cambridge Acoustical Associates
  1   Garrelick

1 J.G. Engineering Research
  1   Greenspan

1 MIT
  1   Dyer

Copies

1 Catholic Univ. of Am. Eng. Dept.
  1   McCoy

2 Boston University
  1   Pierce
  1   Barbone

1 Penn State University
  1   Koopman

2 Virginia Tech
  1   Knight
  1   Fuller

CENTER DISTRIBUTION

Copies	Code	Name
1	011	Corrado
2	0112	Douglas
		Halsall
1	20	
1	2040	Everstine
1	70	Covich
1	701	Sevik
3	7015	Fisher
		Hamly
		Vendittis
1	7020	Strasberg
1	7030	Maidanik
1	7203	Dlubac
7	7250	Shang
		Becker
		Bowers
		Carroll
		Maga
		Niemiec
		Vasudevan
1	842	Graesser
2	3421	(TIC-Carderock)